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Towards Adaptive Prosthetic Sockets using 3D-printed Variable-stiffness Shape-memory Structures

Afonso Pourfarzaneh, Majid Taghavi, Tim Helps and Jonathan Rossiter

Abstract—Many amputees experience pain and soreness due to poor fitting of their prosthetic socket, which is exacerbated by inevitable changes in volume and shape of their residual limb. This work presents an adjustable, adaptive residual-limb-fitting concept: integrating a 3D-printed variable-stiffness (VS) interface layer within the socket. We exploit the glass-transition behaviour of polylactic acid (PLA), demonstrating 3D-printed structures that can be transitioned from a rigid state to a soft state, simply by heating. This not only enables the socket to be adjusted to fit the individual's residual limb, but also allows tuning of its stiffness by changing the internal structure of the interface layer. The mechanical properties of 3D-printed variable-stiffness structures are investigated, and the shape-memory effect of PLA is also captured to deliver 3D-printed shape-memory structures that can recover from deformation when heated.

Index Terms—variable-stiffness, shape-memory effect, 3D printing, prosthetics, orthotics, rehabilitation robotics.

I. INTRODUCTION

Limb-loss is increasing in prevalence, with the numbers expected to more than double between 2005 and 2050 in the USA, reaching 3.6 million amputees [1]. Despite the advances in prosthetic technology and medical care, fitting a prosthetic limb remains a challenging process, particularly when using the commonly chosen inexpensive models. Prosthetists normally require decades of experience to successfully perform this fitting and still require subjective feedback from the patient, there being few alternative, effective methods for measuring fit.

Additionally, most patients experience changes in the volume and shape of their residual limb, as it can swell or contract over time, making it even more challenging to deliver an accurately fitting prosthetic socket. A prosthesis must be stiff and tightly fitted to enable the transmission of large forces (such as those required when walking or lifting heavy objects) but must also remain soft and shock-absorbing to minimise damage to the residual limb. This inevitably introduces undesirable compromises in fit and function that the prosthetist and patient must face together; it is common for amputees to complain about their prosthesis being uncomfortable [2].

Recent developments of 3D-printed variable-stiffness (VS) structures show growing potential in shape-adaption and morphing applications due to their thermally induced,

reversible transition between rigid and soft states [3,4]. This capability enables a broad range of applications in Medicine and Robotics, especially where compliance and safe interaction are required, including prosthetics and rehabilitation robotics [4,5].

Controllable, variable stiffness is typically achieved either by active control of an actuator system (for example in a robot arm) or by controlling the inherent mechanical properties of a material. In this work we adopt the latter approach and seek to control stiffness through active and adaptive materials. Shape-memory alloys or polymers (SMA or SMP) are examples of adaptive stimulus-responsive materials which have the ability of undergoing large reversible deformations upon external stimulation (by heat, electricity, magnetism or application of a solvent) [6]. When heated above glass-transition temperature (T_g), SMPs lose rigidity and can be easily moulded into a new shape, which they will keep after cooling. If re-heated, they automatically recover their original, undeformed shape [7]. Most thermoplastic materials can be employed to obtain VS structures if they change stiffness and acquire a rubbery soft state when heated above their respective T_g , but not all will show a shape-memory effect. PLA filament has been demonstrated to have significant thermally induced stiffness change and a shape-memory effect. The control of PLA structures has been shown by heating through embedded nickel titanium (NiTi) or nickel chromium (NiCr) wires, delivering functionality in wearable structures that require change in rigidity [8,9]. Recent studies have also used 3D-printable conductive PLA filament as a heating element: both conductive and non-conductive materials were printed simultaneously using a dual extrusion 3D printer to produce monolithic VS structures [11].

The aim of this research study is to expand the VS structures paradigm with a focus on its application to prosthetic socket design and fitting techniques, to accomplish better adaptability and customisation for amputees. Prosthetic linings have been identified as a potential application of shape-memory polymers [12]. In this concept, a prosthetic socket would contain a temperature-controlled VS interface layer that can adapt to inter-day and intra-day changes in the shape of the residual limb. Such a socket would also reduce the difficulty in fitting a new prosthetic socket in the clinical setting, reducing patient and clinician stress and increasing the quality of outcomes. To achieve this aim, we will investigate both the

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phase-change aspects of the 3D-printed materials and the structural design of the VS interface layer.

II. METHODOLOGY

A. Concept

The VS layer concept aims to improve the comfort and fit of prosthetic sockets by inclusion of a temperature controlled variable-stiffness interface layer. Since the shape of every residual limb is unique and varies over time, there is a need not only for adaptability, but also for reversibility. Therefore, this work presents a 3D-printed VS interface layer made of thermally responsive PLA that, when heated above its T_g (59.2 ± 1 °C for pure PLA [10]), becomes soft and can adapt to the shape of the residual limb that contacts it. When allowed to cool, the VS layer becomes rigid and stable whilst maintaining its adapted shape, which should deliver an optimal load distribution with respect to the residual limb. PLA also exhibits a shape-memory effect [13]; PLA composites typically exhibit recovery stresses of 1–10 MPa [14]. As such,

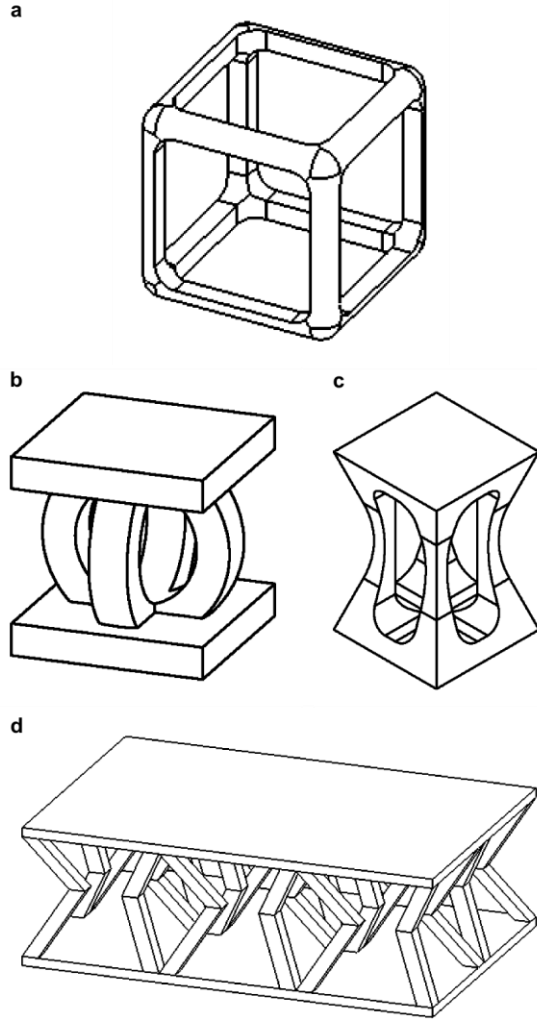


Figure 1. Basic designs used to investigate variable-stiffness interface layers for prosthetic sockets. a) open cubic design with dimensions 80×80×80 mm; b) ‘Sphere’ design with dimensions 30×30×31 mm; c) ‘Bowtie’ design with dimensions 25×25×37.5 mm; d) Prosthetic socket interface layer with dimensions 67.5×45×22.5mm.

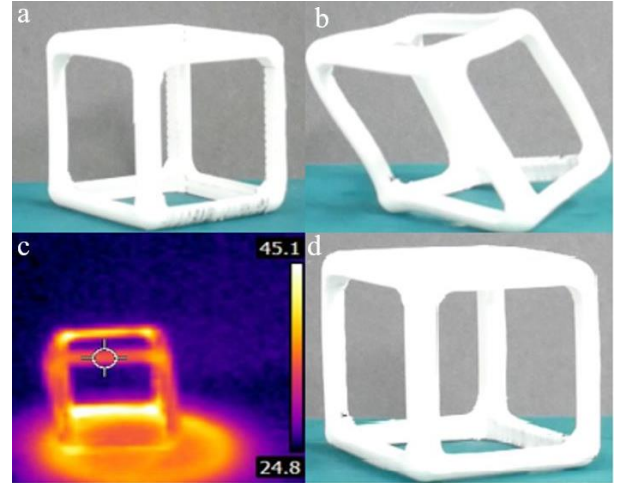


Figure 2. Images showing the shape-memory behaviour of the cubic VS structure. a) initial shape of the cubic VS structure. b) deformed shape of the cubic VS structure after heating above T_g and application of load. c) thermal image after partial heating of cubic VS structure. d) thermally recovered shape of cubic VS structure, demonstrating shape recovery.

the VS layer can be returned to its initial shape simply by heating it while no load is applied to it, thus delivering the reversibility required for adaptive sockets.

B. Design and Fabrication

Four 3D structure designs are presented. The first, an open cubic VS structure (Fig. 1a), was used in initial experiments to observe the shape-memory behaviour of 3D-printed PLA structures. The next two designs (Fig. 1b, 1c), referred to as ‘sphere’ and ‘bowtie’ respectively, were used for isotonic mechanical characterisation to determine their variable-stiffness characteristics. The final design (Fig. 1d) is a planar structure with embedded flexural elements, which enables direct investigation of the application of a variable-stiffness interface layer.

All models were printed using off-the-shelf PLA filament (832-0223, RS Components Ltd, UK) using a 3D printer (Ultimaker 3, Ultimaker, US).

C. Experiments

The concept of a monolithic 3D printable VS structure was first presented by the authors in [11]; thermally responsive graphene PLA was embodied in the structure as a heating element, the temperature of which could be increased by ohmic heating through the graphene ‘wiring’. In this work, we are not explicitly studying monolithic structures with embedded heating elements, rather we focus on the structural behaviour of glass-transition materials. As such, to maximise the simplicity of designs, we fabricated all VS structures using pure PLA and heated them by submersing in hot water to characterise the structures in a uniform environment.

Figure 2 shows initial experiments with the open cubic VS structure to determine the shape recovery potential of 3D-printed PLA. Here the printed cube was vertically loaded and then heated above T_g to initiate deformation and then cooled to room temperature (Fig 2b). Subsequently it was reheated

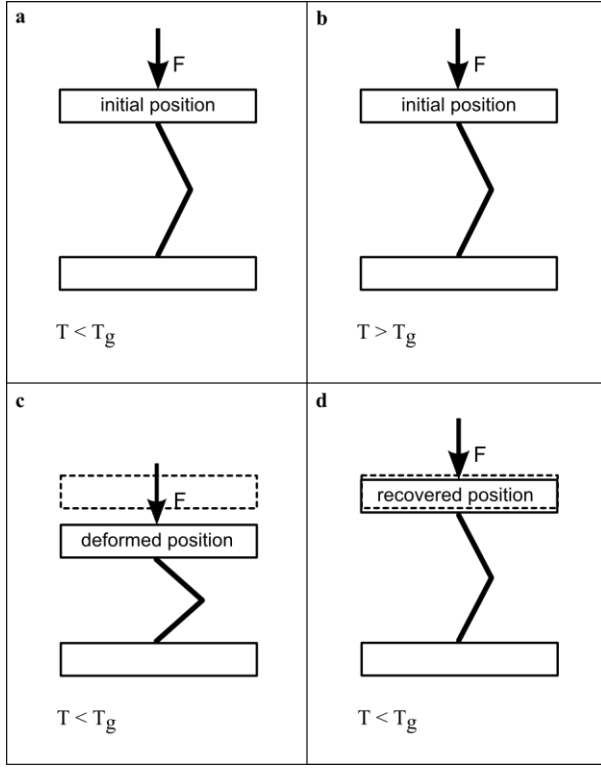


Figure 3. Isotonic characterisation of VS structures. Structures were characterised in four different experimental states. a) S_I : Initial state. Initially undeformed sample at room temperature. b) S_S : Soft state. Initially undeformed sample at $T > T_g$. c) S_D : Deformed state. Deformed sample at room temperature. d) S_R : Recovered state. Recovered sample at room temperature.

under no load (Fig 2c), triggering shape-memory behaviour and causing it to recover its initial shape (Fig. 2d)

Isotonic characterisation (Fig. 3) of the sphere and bowtie models was performed to investigate their stiffness under four conditions. To achieve this, loads ranging from 0.5 kg to 4 kg were consecutively applied to the sample while its deflection under these loads was measured using a precision laser displacement sensor (LK-G152, Keyence, Japan). The stiffness of each sample was measured in four different experimental states $\{S_I, S_S, S_D, S_R\}$:

- S_I : Initial state. Initially undeformed sample at room temperature (Fig. 3a).
- S_S : Soft state. Initially undeformed sample at $T > T_g$ (Fig. 3b).
- S_D : Deformed state. Deformed sample at room temperature (Fig. 3c).
- S_R : Recovered state. Recovered sample at room temperature (Fig. 3d).

During the soft state (S_S), the sample underwent permanent plastic deformation as increasing loads were applied, since the experiments were undertaken above the sample's glass transition temperature. After isotonic experiments in state S_S , the sample was cooled to room temperature, transitioning to a stiff (but deformed) state (S_D). As such, the final deformation resulting from the maximum load during soft state S_S

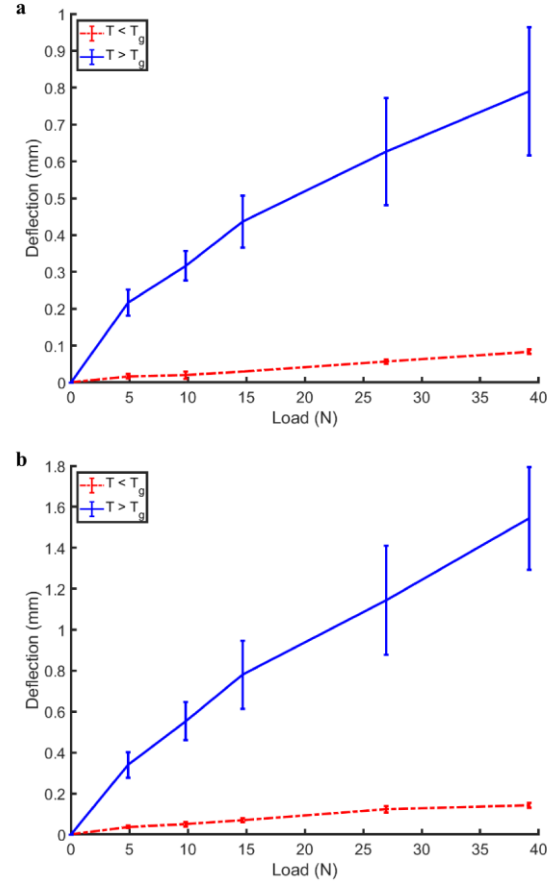


Figure 4. Deflection as load is varied for a) sphere and b) bowtie designs. Points are averages of three samples and error bars show \pm one standard deviation. At room temperature, the designs showed high stiffness (red). When the temperature was increased above T_g the structures became soft and deflection was increased (blue).

determined the deformation of the sample at the beginning of deformed state S_D .

After isotonic testing in state S_D the load was removed from the sample and it was heated above T_g . This resulted in it becoming soft and undergoing shape-memory recovery. It was then allowed to cool into its recovered state, S_R , ready for final isotonic testing.

III. RESULTS AND DISCUSSION

A. Variable-stiffness Behaviour

Figures 4a and 4b show the deflection of the sphere and bowtie VS structures respectively, when isotonic testing was performed under the initial (S_I) and soft (S_S) states. In state S_I (at room temperature) the deflection of both structures was small as the load was increased, reaching only 0.1 mm when 4 kg of load was applied. This demonstrates the strength and rigidity of these VS structures in their room-temperature state.

When the VS structure temperature was increased above the glass-transition temperature of PLA, they transitioned to the soft state (S_S) and considerably higher deflection occurred under loading: the sphere design underwent up to approximately 0.8 mm deflection and the bowtie design

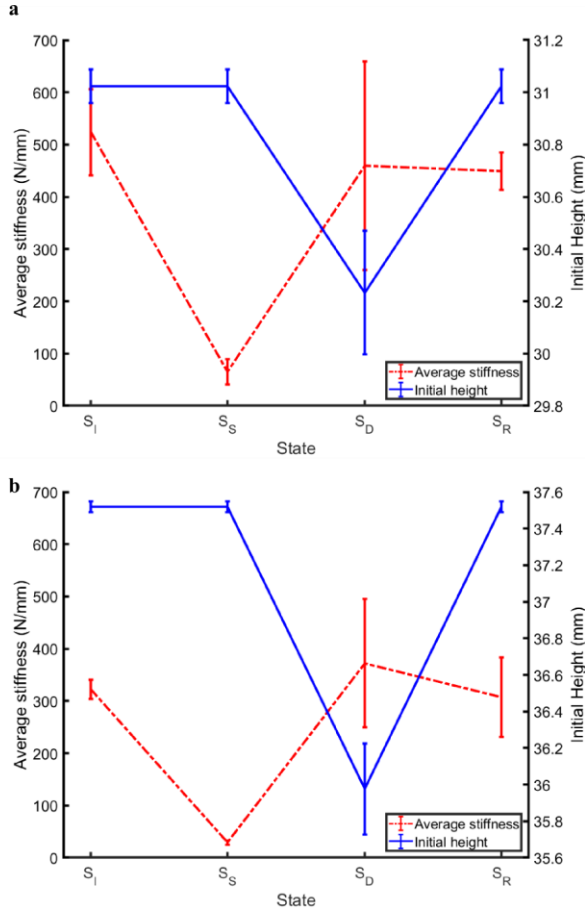


Figure 5. Average stiffness and initial height for a) sphere and b) bowtie designs. Points are averages of three samples and error bars show \pm one standard deviation. Average stiffness was high for both designs in all experimental states other than the soft state S_S . In deformed state S_D the VS structure had been compressed by the applied load while in state S_S , resulting in the low initial height. In the recovered state S_R the VS structure had been heated above its glass-transition temperature while under no load, and exhibited almost complete shape recovery approaching its initial (undeformed) shape.

underwent up to approximately 1.6 mm deflection, representing an increase in strain of 1500% compared to state S_I .

Using data from isotonic testing, the stiffness of the sphere and bowtie designs under each experimental state was determined. Average stiffness was calculated by dividing maximum deflection by maximum load. Figures 5a and 5b show average stiffness in each experimental state.

Average stiffness was high in states S_I , S_D and S_R , at around 480 N/mm for the sphere design and around 330 N/mm for the bowtie design. In contrast, average stiffness was considerably lower during soft state S_S : approximately 65 N/mm for the sphere and 29 N/mm for the bowtie design. This variation in stiffness is consistent with the glass-transition behaviour of PLA. These experiments confirm the suitability of PLA and other glass-transition materials to deliver the variable-stiffness behaviour that is required for the VS layer concept.

B. Shape-memory Behaviour

Figure 5a and 5b also show initial height, the height of the VS structure at the start of each experimental state. The initial height at the beginning of state S_D shows how much the VS structure was permanently deformed during the previous experiment in state soft S_S .

As previously mentioned, residual limbs can change in both volume and shape, both in the short-term (within a day) and in the long-term (over multiple months). In the case of residual limb growth or shape change, the adaptive layer should adapt to properly accommodate the limb's new shape. The experiments shown here demonstrate the compliance and adaptability of the VS structures when in soft state, and how this shape can be 'locked' by simply transitioning to the room-temperature rigid state.

Furthermore, for the concept proposed in this work it is important that the interface layer demonstrates shape-memory behaviour. In the case that the residual limb shrinks or changes shape, the interface layer should expand or grow (i.e. recover towards its initial as-fabricated shape), such that no voids exist surrounding the residual limb. This can be achieved if the interface layer exhibits shape-memory behaviour. The initial height at the beginning of the recovered state S_R (Fig. 5) shows the height of the VS structure after it had been heated above its glass-transition temperature while under no load. Both structures (sphere and bowtie) exhibited considerable shape-memory behaviour when heated, recovering more than 99% of their initial height. This confirms that the shape-recovery behaviour that these structures can deliver is considerable and demonstrates the high suitability of 3D-printed glass-transition material structures for use in adaptive interface layers.

C. Variable-stiffness interface layer

As a final demonstration, the interface layer design (Fig. 1d) was used to simulate the behaviour of an adaptive interface layer interacting with a residual limb. A rod with one rounded end (22 mm diameter) was 3D-printed to emulate the residual limb (Fig 6a).

The emulated limb was pressed against the interface layer with a load of 1 kg. When the interface layer was at room temperature (state S_I), it remained hard and rigid, demonstrating the strength and stiffness required for load-bearing applications.

When the interface layer was heated above its glass-transition temperature, it transitioned to soft state S_S . Its stiffness reduced considerably, demonstrating the softness

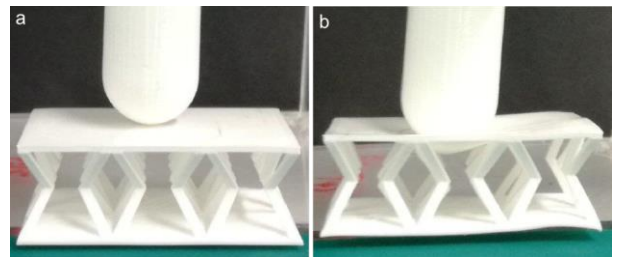


Figure 6. Demonstration of the adaptive interface layer: a) interface layer at room temperature; b) interface layer after heating above T_g and deformed by pressing the 3D-printed residual limb into it.

required for comfort, reducing point loads on the emulated residual limb. The interface layer was deformed by the load exerted by the emulated residual limb, moulding to its shape (Fig. 6b). The structure was then transitioned to its rigid deformed state (S_D) by cooling to room temperature.

When the emulated residual limb was removed, the interface layer retained its deformed shape, demonstrating its ability to be permanently moulded to the new shape of the residual limb. This behaviour is expected to significantly improve the prosthetic fitting process.

Finally, the interface layer was once again heated above its T_g temperature with no load applied. The interface layer exhibited shape recovery behaviour and transitioned back to its initial, undeformed shape. This behaviour shows how the interface layer could recover to properly encapsulate a residual limb which has changed shape or shrunk. The reversible deformation behaviour of this novel adaptive interface layer could also allow re-usable temporary sockets (test sockets that are used during the fitting process before creating permanent moulded sockets) that exhibit useful shape-adapting and shape-memory behaviour.

The experiments presented here capture the fundamental adaptive interface layer concept, demonstrating temperature-controlled variable-stiffness behaviour, reversible deformability and shape recovery. While the surface of the interface layer should be flat in order to interface most effectively with the skin of the residual limb, the structure beneath its surface can be modified to alter the mechanical behaviour of the structure. The internal zig-zag structure used here (Fig. 6) results in nonlinear elastic behaviour as load is

applied and the structure bends. Alternative interface layer designs could be used to deliver more sophisticated elastic behaviour, allowing the passive compliance of the interface layer to increase (strain-stiffening) or decrease (strain-softening) as a function of compression.

The use of auxetic structures in place of the zig-zag interface layer design could provide a wide range of interesting and beneficial geometrical behaviours. They could be used to optimise shape-memory behaviour, improve the strength of the interface layer or even intelligently respond to varying loading conditions.

A considerable advantage of the VS interface layer presented here is its ability to improve the comfort of a prosthetic socket. Depending on the shape of the user's residual limb, a traditional passive socket can result in high loads being applied locally (Fig. 7a). These can cause discomfort or even injury if they occur long term. With the VS interface layer presented in this article, by transitioning to a soft state the interface can mould itself to exactly match the shape of the residual limb (Fig. 7b). This will result in a more uniform pressure being applied to the surface of the residual limb, minimising point loading, maximising comfort and reducing the chance of injury.

IV. CONCLUSION

This work presents and demonstrates a new concept for prosthetic sockets by exploiting 3D-printed variable stiffness materials to deliver adaptive interface layers. Thermally-controlled shape adaptive materials enable the design of an interface layer that can adjust and morph to match the shape of the residual limb. This allows the socket to overcome several obstacles associated with prosthetic limbs including poor fit, discomfort and low adaptability. Currently, prosthetics that no longer fit the user comfortably are discarded, whereas using this technology their fit can be adapted, increasing their useful lifetime. The technology presented here could also reduce the time associated with fitting a new prosthetic. Most importantly, shape-adaptive VS materials can be used to make interface layers that adapt to the changing shape of the residual limb, which can grow, shrink and morph both during the day and over the longer term.

In the future, research will be undertaken to optimise the geometry of the VS interface layers. The heating method will be encapsulated within the interface layer, for example by exploiting 3D printable graphene composites [9], and the material will be optimised to deliver the best variable stiffness behaviour. This technology presents a wide array of benefits to the field of prosthetics, robotics and beyond.

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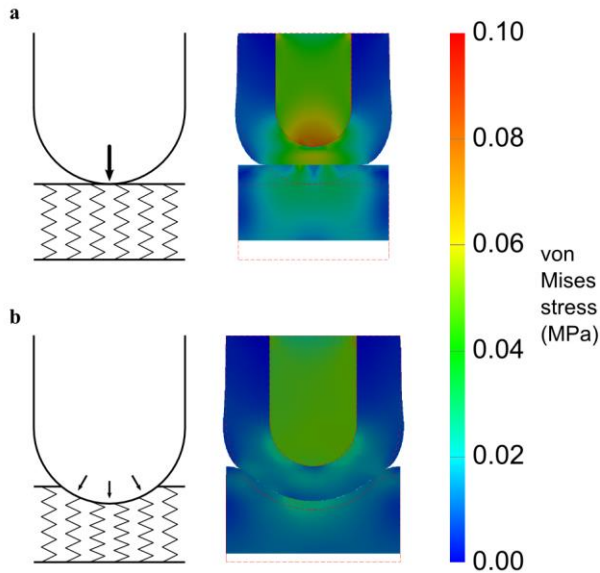


Figure 7. Local loading on a residual limb. a) with a passive prosthetic socket; high loads at certain locations on the residual limb can cause discomfort or injury. b) The VS interface layer presented here can mould to the shape of the residual limb, resulting in a uniform applied pressure. Shown alongside are results from FEA simulation of a residual limb (bone and tissue) resting on a PLA interface layer under a load of 3 N. Young's modulus used for bone, tissue and PLA: 17600 MPa, 0.1 MPa and 3500 MPa respectively. Poisson's ratio used for bone, tissue and PLA: 0.3, 0.45 and 0.35 respectively. The moulded interface layer imposes considerably lower stresses on both bone and tissue.

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